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PREDICTION OF ENGINE EXHAUST CONCENTRATIONS DOWNWIND FROM THE DELTA-THOR TELSAT-A LAUNCH OF NOVEMBER 9, 1972

by John W. Kaufman, Michael Susko, and C. Kelly Hill

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16. ABSTRACT

Presented in this report are the results of the downwind concentrations of engine exhaust by-products from the Delta-Thor Telsat-A vehicle launched from Cape Kennedy, Florida on November 9, 1972 (2014 EST). The meteorological conditions which existed are identified as well as the exhaust cloud rise and the results from the MSFC Multilayer Diffusion Model calculations. These predictions are herein compared to exhaust cloud sampled data acquired by the Langley Research Center personnel. Values of the surface level concentrations show that very little hydrochloric acid (HCl), carbon monoxide (CO), or aluminum oxide (Al_2O_3) reached the ground.

*A companion report is being prepared by Langley Research Center personnel entitled "Effluent Sampling of Scout D and Delta Launch Vehicle Exhaust" by William C. Hulten, Richard W. Storey, Jr., Gerald L. Gregory, David C. Woods, and Franklin S. Harris., Jr. The report will be available in the very near future.

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DEFINITION OF SYMBOLS

Symbol		Definition
F_C	=	buoyancy flux
	=	$\frac{gQ_F}{\pi\rho c_p T}$
F_I	=	initial buoyancy term
	=	$\frac{3gQ_I}{4c_p T\pi\rho}$
FM	=	percentage by weight of pollutant material in the fuel from Table 1
H_L, H_S	=	respective heat contents of liquid and solid fuels
L	=	depth of the surface mixing layer
M	=	molecular weight
P	=	ambient pressure (mb)
$P\{z_{TK}\}$	=	integral of the Gaussian probability function between minus infinity and the top of the K-th layer z_{TK}
	=	$P\left\{\frac{z_{TK}-z_{mI}}{\sigma}\right\}$
Q	=	total weight of exhaust products in the stabilized exhaust cloud
	=	$\left(Q_R\right)\left(t_R\left\{z_{mI}\right\}\right)\left(FM\right)$
Q_F	=	rate of heat released by burning fuel
	=	$H_L \bullet W_L + H_S \bullet W_S$

DEFINITION OF SYMBOLS (continued)

Symbol		Definition
Q_I	=	effective heat released (cal)
$\dot{Q}_K$	=	source strength in units of mass per unit depth of the K-th layer
Q_R	=	fuel expenditure rate from Table 1
T	=	ambient air temperature (^oK)
W_L, W_S	=	respective fuel expenditure rates for liquid and solid fuel
z	=	height above ground of any selected layer
c_p	=	specific heat of air at constant pressure cal/(^{o}Kgm)
g	=	gravitational acceleration (9.8 m/sec^2)
r_R	=	initial cloud radius at the surface
$s = \frac{g}{T}\frac{\partial\Phi}{\partial z}$	=	stability parameter
t^*	=	time of layer breakdown
t_H	=	time after ignition required for the cloud to reach the stabilization height
t_R	=	time after ignition in seconds
$t_R z_{mI}$	=	time in seconds required for the vehicle to reach the height z_{mI} of maximum rise of the ground cloud (obtained from Equation 1)
$\bar{u}$	=	mean wind speed
z	=	height of stabilized cloud
z'	=	midpoint of the K-th layer
	=	$\left(z_{BK} + z_{TK}\right)/2$

DEFINITION OF SYMBOLS (continued)

z_{BK}	=	height of the base of the K-th layer
z_{BL}	=	height of the base of the L-th layer
z_L	=	height in the L-th layer at which the concentration is calculated
z_{mC}	=	maximum height of cloud rise for a continuous source
z_{mI}	=	maximum rise for an instantaneous source
z_{TK}	=	height of the top of the K-th layer
z_{TL}	=	height of the top of the L-th layer
z_R	=	altitude above the pad in meters
γ_C	=	entrainment constant (continuous)
γ_I	=	entrainment constant (instantaneous)
σ	=	standard deviation of the concentration distribution of the stabilized ground cloud
σ_{xK}	=	standard deviation of the alongwind concentration distribution in the K-th layer at distance x
σ_{xLK}	=	standard deviation of the alongwind concentration distribution in the L-th layer for the source originating in the K-th layer
$\sigma_{xo}\{K\}$	=	standard deviation of the alongwind concentration distribution in the K-th layer at cloud stabilization
$\sigma_{yo}\{K\}$	=	standard deviation of the crosswind concentration distribution in the K-th layer at cloud stabilization

DEFINITION OF SYMBOLS (Continued)

Symbol		Definition
$\sigma_{zo}\{K\}$	=	standard deviation of the vertical concentration distribution in the K-th layer at cloud stabilization
σ_{yK}	=	standard deviation of the crosswind concentration distribution in the K-th layer at distance x
σ_{yLK}	=	standard deviation of the crosswind concentration distribution in the L-th layer for the source originating in the K-th layer
σ_{zLK}	=	standard deviation of the vertical concentration distribution in the L-th layer for the source originating in the K-th layer
ρ	=	density of ambient air (g/m^3)
$\frac{\partial\Phi}{\partial z}$	=	vertical gradient of ambient potential temperature
χ_p	=	peak or centerline concentration

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SUMMARY

The study of the engine exhaust by-products from the Delta-Thor Telsat-A vehicle has made a significant contribution to the understanding of the dynamics of such hot buoyant clouds. Predictions made of the ground cloud rise were satisfactory and the dispersion characteristics were calculated. Although the emission source from the Delta-Thor is limited due to the smallness of the vehicle a sufficient amount of data were available to study the behavior of exhaust material in the atmospheric mixing layer. In that the calculations show the maximum centerline peak concentrations of HCl were only about 1.0 ppm, no real toxic condition could have resulted.

Additional work should be done to examine the behavior of future Delta-Thor exhaust emissions and other vehicle exhausts to properly understand the atmospheric diffusion of such effluents. This is needed to determine launch constraints for all vehicles which emit nuisance type exhaust by-products.

SECTION I. INTRODUCTION

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1.1 Background

Estimates have been made of the exhaust emission concentrations downwind from the Delta-Thor Telsat-A vehicle launched on November 9, 1972 from Cape Kennedy. The results were obtained by using the MSFC Multilayer Diffusion Models 1 & 5 [1] or Models 1 and 4 of the revised report [2]. Compounds from the solid rocket engines of concern were HCl, CO, and Al_2O_3. Pollutant concentrations were calculated at ground level and at heights above ground corresponding to the flight altitudes at which the sampling aircraft operated by Langley Research Center penetrated the diffusing ground cloud. Source data used in deriving source model inputs were obtained from personnel at MSFC and Langley Research Center, and from the engine manufacturers. Meteorological data used in the calculations were obtained from a rawinsonde released from Cape Kennedy near the time of the launch and from measurements made on the NASA 150 Meter Ground Wind Tower at KSC [3].

1.2 Propellant Properties and Vehicle Rise Data

The first stage of the Delta-Thor Telsat-A vehicle used in this launch was comprised of a liquid-fueled engine and six solid-fuel strap-on engines. Propellant properties of the Delta-Thor engines are shown in Table 1. The propellant expenditures rates given in the table are average rates over the total burn times shown in Table 1. The propellant heat contents in Table 1 are based on estimates obtained from the engine manufacturers, and do not include heat generated by recombination of chemical radicals as the exhaust cloud cools to ambient temperature or the heat due to kinetic energy. The propellant heat contents in the table were used in the calculations of cloud rise, and it was found that these data were in good agreement with existing measurements from liquid-fueled and solid-fueled exhaust emissions [4 through 14]. It should be noted, however, that cloud rise measurements were not availalbe for launches of vehicles with first stages comprised of both liquid- and solid-fueled engines.

The altitude-time curve of the Delta-Thor Telsat-A is also required to compute the rise of the ground cloud of exhaust products. Figure 1 shows a plot of vehicle altitude versus time after ignition. A logarithmic least-squares regression curve fitted to the data shown in Figure 1 yields the expression

$$t_R = 1.32095 z_R^{0.39457}$$

TABLE 1.

PROPELLANT PROPERTIES OF THE DELTA-THOR FIRST-STAGE*

Propellant Expenditure Rate (g/sec)	
Liquid Engine	3.13256×10^5
Six Solid Motors	6.04367×10^5
Total Burn Time (sec)	
Liquid Engine	212
Solid Motor	37
Propellant Heat Content (cal/g)	
Liquid Propellant	500
Solid Propellant	691
Propellant Composition (percent by weight)	
Liquid Propellant	
CO	47.30
Solid Propellant	
HCl	20.83
CO	22.26
Al_2O_3	37.77

*Data were obtained through personal communication with United Technology Center, Division of United Aircraft, Sunnyvale, California, November 1972.

which relates that the time after lift off (t_R) is a function of the altitude of the vehicle above pad (z_R).

1.3 Organization of the Technical Memorandum

Section 2 contains a description of the meteorological measurements made at the time of the Delta-Thor Telsat-A launch on November 9, 1972. Section 3 describes the cloud rise calculations for the launch. The cloud dimensions and vertical distribution of exhaust products in the ground-cloud produced by the Delta-Thor Telsat-A launch are discussed in Section 4. The MSFC Multilayer Diffusion Models used in the calculation of concentrations downwind from the launch are briefly described in Section 5. The results of the calculations are given in Section 6.

SECTION 2. METEOROLOGICAL MEASUREMENTS FOR THE DELTA-THOR LAUNCH

Rawinsonde measurements were made at Cape Kennedy throughout the day preceeding the launch of the Delta-Thor vehicle at 2014 EST on November 9, 1972. All the measurements indicated the presence of a marine inversion over the Cape Kennedy area with the base of the inversion near 900 meters above the surface and the top of the inversion at heights of 1300 to 1500 meters. The temperature lapse rate from the surface to the base of the marine inversion was approximately dry adiabatic throughout the day. During the early evening, a surface-based inversion began to form over the land. By 2014 EST, this inversion was about 150 meters in depth. The temperature and wind speed profiles in the lowest 2000 meters measured by the rawinsonde released at 2018 EST are shown in Figure 2. Inspection of Figure 2 shows that wind speed at all heights in the lowest 2000 meters did not exceed 4 meters per second. At the surface, winds were nearly calm. Wind speed increased through the surface inversion to 4 meters per second at the top of the inversion, then remained nearly constant to the height of the marine inversion base. Wind speed decreased with height in the marine inversion.

The launch site of the Delta-Thor vehicle is situated at the shoreline two miles south of the location where the rawinsonde is released. For this reason, the surface-based inversion indicated by the rawinsonde data may not have been present above the launch site or below the initial downwind trajectory of the exhaust cloud. Concentrations were, therefore, calculated for both the case where the surface-based inversion was present and the case where no inversion was present. The dashed lines in Figure 2 show modifications in the rawinsonde profiles used in the calculations where the surface-based inversion was not considered. The wind speed profile was modified between the heights of 800 and 1200 meters so the computer program would calculate a mean wind speed in layer between 200 and 900 meters representative of the observed mean wind speed in this layer.

Figure 3 shows the vertical temperature and wind speed profiles measured at the NASA 150 Meter Ground Wind Tower at launch time. This tower is located about 13 miles north-northwest of Launch Complex 17. These measurements agree with the rawinsonde data, and were used to specify the wind speed and temperature profiles in the lowest 150 meters for the case in which the surface-based inversion was assumed to be present at the launch site. The value of the 10 minute standard deviation of azimuth wind angle of 9 degrees used in the calculation was obtained from the tower measurements.

Figure 4 shows the wind direction profile measured by the rawinsonde and the 150 m Ground Wind Tower at T+4 minutes. Rapid changes in the large-scale wind field were occurring in the lower atmosphere at this time. This condition plus some overriding effects of the sea breeze produced a situation, whereby, wind direction profile differences in the lowest 1 km altitude were likely across Cape Kennedy, especially, between the coastline and points inland. Within the marine inversion the direction veered with height from 130 degrees at the base to 230 degrees at the top of the inversion. The direction below the marine inversion was nearly constant from approximately 130 degrees at the base to 230 degrees at the top of the inversion. The direction below the marine inversion was nearly constant from approximately 130 degrees within the 300-900 meter altitude layer. Between the ground and 300 meters the wind veered sharply from 220 degrees to about 130 degrees. The wind direction prediction of 035 degrees in the ground to 700 meter layer was valid only for the original launch time of 1758 EST. The rapid changes in the wind field beginning about this time made the forecast prepared for 1758 EST not truly applicable for the launch at 2014 EST since there was about a 2 hour delay. A time-height cross-section analysis of a sequence of wind profile indicates that a wind direction of about 050 degrees over the rawinsonde site likely occurred at the originally scheduled launch time. Thus, the predicted 035 degrees compares favorably with the analyzed 050 degrees for the original launch time wind direction; however, the fact that the actual measured wind direction after the delay was 130 degrees demonstrates the criticality of time in atmospheric predictions. It is quite reasonable to expect from this atmospheric situation described that the exhaust ground cloud may have drifted along a somewhat different trajectory than might be inferred from a strict application of the rawinsonde profile data.

The meteorological inputs used in the calculations are given, along with the source model inputs described in Sections 3 and 4 below, in the Appendix. The Appendix also contains a description of the rationale used to specify the vertical profiles of $\sigma_A\{\tau_{oK}\}$ and σ_E required for use in the MSFC Multilayer Diffusion Model Program.

SECTION 3. CLOUD RISE CALCULATIONS

The burning of rocket engines during normal launches results in the formation of a cloud of hot exhaust products which subsequently rises and entrains ambient air until an equilibrium with ambient conditions is achieved. Experience to date shows that the buoyant rise of exhaust clouds from normal launches of large liquid-fueled vehicles is best predicted by using a cloud rise model for continuous sources. This is probably explained by the relatively long vehicle residence time on the pad after ignition and just above the pad. On the other hand, experience in predicting the buoyant rise from normal launches of solid-fueled vehicles indicates the rise is best predicted using a cloud rise model for instantaneous sources. For solid-fueled vehicles residence times near the pad are relatively short. Measurements of cloud rise from launches of Delta-Thor vehicles were not available. Since the first-stage of the Delta-Thor vehicle is comprised of both solid-fueled and liquid-fueled engines, there is some question which formula, continuous or instantaneous, yields appropriate cloud rise estimates. In this case, a decision was made to calculate the rise using both formulas and to use the average of the two as an estimate of cloud rise. In the calculation of cloud rise with the two formulas, the temperature structure indicated by the dashed lines in Figure 2 was used, principally because the shallow surface-based inversion would have little effect in inhibiting cloud rise.

The maximum rise z_{mI} for an instantaneous source is given by the expression

$$z_{mI} = \left[\frac{8F_I}{\gamma_I^3 s} + \left(\frac{r_R}{\gamma_I} \right)^4 \right]^{1/4} - \frac{r_R}{\gamma_I} \qquad (1)$$

In deriving Equation (1), it is assumed that the initial upward momentum imparted to the exhaust gases by reflection from the ground surface and launch pad hardware is insignificant in comparison with the effect of thermal buoyancy. Based on limited experience in predicting cloud rise from launches at Vandenberg Air Force Base, this assumption appears to be justified. The time required for the cloud to reach the stabilization height is given by the expression

$$t_H = \frac{\pi}{s^{1/2}} \qquad (2)$$

In calculating z_{mI} from Equation (1), the instantaneous heat released Q_I is obtained from the relationship

$$Q_I = Q_F \, t_R \{z_{mI}\} \tag{3}$$

Inspection of the equations given above reveals an interdependence between the calculated maximum cloud rise z_{mI}, the height over which the potential temperature gradient $\partial\Phi/\partial z$ is measured, and the value of $t_R\{z_{mI}\}$ used in obtaining Q_I. Thus, the final value of maximum cloud rise must be found through iteration of Equation (1). The height over which $\partial\Phi/\partial z$ is measured and the time $t_R\{z_m\}$ are thus made consistent with the value of z_{mI} calculated from the model.

The maximum cloud rise from a continuous source z_{mC} is given by

$$z_{mC} = \left[\frac{6\,F_C}{\bar{u}\,\gamma_C^2\,s} + \left(\frac{r_R}{\gamma_C}\right)^3\right]^{1/3} - \frac{r_R}{\gamma_C} \tag{4}$$

Equation (4), as in the case of Equation (1) for an instantaneous source, assumes the initial momentum flux imparted to the plume by dynamic forces can be ignored in the calculation of maximum cloud rise. Again, experience in calculating cloud rise for normal launches of large liquid-fueled rockets and for static firings has shown that this assumption is reasonable. Equation (4) must also be iterated to obtain the final value of z_{mC}, since $\partial\Phi/\partial z$ must be estimated over the height of final rise.

In the calculations, the parameter r_R for the Delta-Thor Telstat-A launch was set to zero, γ_I was set to 0.64, and γ_C was set to 0.5 for consistency with experience in predicting cloud rise from other normal vehicle launches. The mean wind speed $\bar{u}$ in Equation (4) was set equal to 3.3 meters per second and the value for the ρ used in both calculations was 1218 grams per cubic meter. The use of Equation (1) resulted in an estimate of z_{mI} of 460 meters and the use of Equation (4) resulted in an estimate of z_{cI} of 1035 meters. The average of these two estimates, 747 meters, was used as the predicted height of the centroid of the stabilized ground cloud in the concentration calculations and in the calculation of the source dimensions and vertical distribution of exhaust products described in Section 4 below.

SECTION 4. CLOUD DIMENSIONS AND VERTICAL DISTRIBUTION OF EXHAUST PRODUCTS FOR THE DELTA-THOR LAUNCH

Source inputs required for the diffusion model calculations include the stabilization height of the exhaust cloud and cloud dimensions, as well as the vertical distribution of exhaust products in the stabilized cloud. The calculation of the stabilization height z_m is described in Section 3 above. The calculation of the dimensions of the stabilized cloud and the vertical distribution of exhaust products is described below.

4.1 Dimensions of the Exhaust Cloud at Stabilization

Figure 5 shows the calculated dimensions of the stabilized cloud of exhaust products for the launch of the Delta-Thor Telstat-A vehicle on November 9, 1972. The stabilization height z_m was calculated to be 747 meters as described in Section 3 above. The general formula used to calculate the radius of the stabilized cloud at height z is given by the expression

$$r\{z\} = \left\{ \begin{array}{ll} \gamma z & ; \; z \leq z_m \\ \gamma (2 z_m - z) \geq 200 \text{ meters}; & z \geq z_m \end{array} \right\} \qquad (5)$$

where $\gamma = (\gamma_I + \gamma_C) / 2 = 0.57$

Note that for $z > z_m$, the minimum radius of the stabilized cloud is set equal to 200 meters.

As shown in Figure 5, the atmosphere for the Delta-Thor Telsat-A launch was divided into 11 layers between the surface and 2000 meters. The lowest kilometer was subdivided into a greater number of layers because the sampling aircraft penetrations of the exhaust cloud were limited to altitudes below this height. The cloud is assumed to be symmetrical about a vertical axis through the cloud centroid. The alongwind and crosswind source dimensions of the cloud in each of the eleven layers were calculated under the following assumptions:

- The distribution of exhaust products within the cloud is Gaussian (see Section 4.2 below) in the plane of the horizon

- The concentration of exhaust products at a lateral distance of one radius from the cloud vertical axis is 10 percent of the concentration at the cloud axis

The alongwind and crosswind source dimensions required for input to the MSFC Diffusion Models are defined for each layer by

$$\sigma_{xo}\{K\} = \sigma_{yo}\{K\} = \begin{cases} \gamma\, z' / 2.15 & ; z' \leq z_m \\ \gamma\,(2z_m - z')\;/\,2.15 \geq 93 \text{ meters} & ; z \geq z_m \end{cases} \qquad (6)$$

where

z' = midpoint of the K-th layer

$= \left(z_{BK} + z_{TK}\right)/2$

The quantities z_{TK} and z_{BK} are, respectively, the height of the top and base of the K-th layer.

The corresponding vertical source dimension for each layer was calculated from the expression

$$\sigma_{zo}\{K\} = \left(z_{TK} - z_{BK}\right)/\sqrt{12} \qquad (7)$$

Equation (7) applies to a rectangular material distribution which has been assumed to apply along the vertical in the K-th layer.

The source dimensions σ_{xo}, σ_{yo}, and σ_{zo} calculated from Equations (6) and (7) for the Delta-Thor Telsat-A launch are included in the model input tables in the Appendix.

4.2 Calculation of the Vertical Source Strength Distribution in the Stabilized Exhaust Cloud

The fraction of material by weight in each of the K layers $F\{K\}$ for the Delta-Thor Telsat-A launch was calculated from the expression

$$F\{K\} = \begin{cases} Q\,P\{z_{TK}\} & ; \quad K = 1 \\ Q\left(P\{z_{Tk}\} - P\{z_{BK}\}\right) & ; \quad K > 1 \end{cases} \qquad (8)$$

$P\left\{z_{BK}\right\}$ = is the integral of the Gaussian probability function between minus infinity and the base of the K-th layer z_{BK}, and is equal to $P\left\{z_{BK} - z_{mI}/\sigma\right\}$. Sigma ($\sigma$) is equal to $\gamma\left\{z = z_{mI}\right\}/2.15$.

The MSFC Diffusion Models described in Section 5 below require that source strength in each of the K layers be specified per unit height. Since the desired concentration units for HCl and CO are parts per million, the complete expression for the source strength model input for the K-th layer is

$$Q_K = \left(\frac{F\{K\}}{\left(z_{TK} - z_{BK}\right)}\right)\left(\frac{10^3 \text{ mg}}{\text{g}}\right)\left(\frac{22.4}{M}\right)\left(\frac{T}{273.16}\right)\left(\frac{1013.2}{P}\right) \quad (9)$$

For Al_2O_3, the desired concentration units are milligrams per cubic meter and the complete expression for source strength in the K-th layer is

$$Q_K = \frac{F\{K\}}{\left(z_{TK} - z_{BK}\right)}\left(\frac{10^3 \text{ mg}}{\text{g}}\right) \quad (10)$$

Equations (8), (9), and (10) were used to obtain the model input values of Q_K for the various meteorological regimes. These values of Q_K are tabulated in the Appendix.

4.3 Surface Cloud

Photographs of the surface exhaust cloud show that a significant amount of darker exhaust effluent remained next to the ground. At 10 seconds the approximate height of the cloud was 50 meters and the diameter was about 200 meters. After 50 seconds, it was about 250 meters in height and 300 m in diameter. The general consensus of opinion is that this was cooler exhaust by-products which were trapped in the surface inversion where it was transported downwind. This phenomena is not uncommon and is frequently witnessed to occur during static testing and launching of many different vehicles. Subsequently, added stress is being placed on the study of the cold surface clouds generated from aerospace vehicle exhaust emissions.

SECTION 5. MSFC MULTILAYER DIFFUSION MODELS

As mentioned above, the purpose of this study is to calculate concentrations downwind from the launch pad area at the height of the aircraft sampling flights and at ground level for the Delta-Thor Telsat-A launch of November 9, 1972. To make these calculations, we have used Models 1 and 5 of the MSFC Multilayer Diffusion Models described in detail by Dumbauld, *et al.* (1) or by Models 1 and 4 in the revised report (2). Important features of the Models are summarized below. Model 1 has principally been used to calculate centerline concentrations in thermally stable layers and Model 5 and 4, respectively, have been used to calculate centerline concentrations in thermally neutral and unstable layers. The particular model used in each of the K layers is identified in the model input tables presented in the Appendix.

5.1 Model 1

In Model 1, the source is assumed to extend vertically through the layer K, the vertical distribution of material is assumed to be invariant within the layer, and the alongwind and crosswind distributions of material are assumed to be Gaussian. In addition, all the material initially contained in the layer K is constrained from diffusing vertically beyond the upper and lower layer boundaries. As noted above, this model has been used in the present study to calculate pollutant concentrations in thermally stable layers.

In Model 1, the peak or centerline concentration in the K-th layer at some distance x downwind from the source is given by the expression

$$\chi_p = \frac{Q_K}{2\pi\, \sigma_{yK}\, \sigma_{xK}} \tag{11}$$

The subset of equations defining σ_{yK} and σ_{xK} are given on pages 14 through 20 of Reference 1 and pages 22 through 26 of Reference 2. Briefly, σ_{yK} and σ_{xK} are calculated by means of simple power-law expressions relating turbulence parameters to cloud growth with distance.

5.2 Models 5 or 4, Respectively

Model 5 or 4, respectively (see Section 5, 1st paragraph), the layer-transition model described, was principally used to calculate centerline concentrations in thermally neutral or unstable layers because it provides for the requisite vertical mixing and for identifying the

contribution of the material contained in each initial sublayer. The formula for the peak or centerline concentration is given by the expression

$$\chi_{PL} = \frac{Q_K}{4\pi\,\sigma_{yLK}\,\sigma_{xLK}} \Bigg\{ \sum_{i=0}^{\infty} \Bigg[\mathrm{erf}\left(\frac{2i\left(z_{TL}-z_{BL}\right)-z_{BK}+z_L}{\sqrt{2}\,\sigma_{zLK}}\right)$$

$$+\,\mathrm{erf}\left(\frac{2i\left(z_{TL}-z_{BL}\right)+z_{TK}-z_L}{\sqrt{2}\,\sigma_{zLK}}\right) + \mathrm{erf}\left(\frac{2i\left(z_{TL}-z_{BL}\right)+2z_{BL}-z_{BK}-z_L}{\sqrt{2}\,\sigma_{zLK}}\right)$$

$$+\,\mathrm{erf}\left(\frac{2i\left(z_{TL}-z_{BL}\right)-2z_{BL}+z_{TK}-z_L}{\sqrt{2}\,\sigma_{zLK}}\right)\Bigg] + \sum_{i=1}^{\infty}\Bigg[\mathrm{erf}\left(\frac{-2i\left(z_{TL}-z_{BL}\right)-z_{BK}+z_L}{\sqrt{2}\,\sigma_{zLK}}\right) \tag{12}$$

$$+\,\mathrm{erf}\left(\frac{-2i\left(z_{TL}-z_{BL}\right)+z_{TK}-z_L}{\sqrt{2}\,\sigma_{zLK}}\right) + \mathrm{erf}\left(\frac{-2i\left(z_{TL}-z_{BL}\right)+2z_{BL}-z_{BK}-z_L}{\sqrt{2}\,\sigma_{zLK}}\right)$$

$$+\,\mathrm{erf}\left(\frac{-2i\left(z_{TL}-z_{BL}\right)-2z_{BL}+z_{TK}+z_L}{\sqrt{2}\,\sigma_{zLK}}\right)\Bigg]\Bigg\}$$

In application, the surface mixing layer is first divided into a number of sublayers K to accommodate the vertical distribution of pollutants as well as height variations in meteorological parameters. The material contained in these K layers is then allowed to mix vertically across layer boundaries to form a new layer L equal in depth to the surface mixing layer. The formulas for calculating σ_{xLK} and σ_{zLK} are of the same form as those used to define σ_{xK}, σ_{yK} , and σ_{zK} and are given on pages 26 through 33 of Reference 1 and on pages 35 through 39 of Reference 2.

SECTION 6. RESULTS OF THE CALCULATIONS

The results of the model calculations using the MSFC Multilayer Diffusion Model Program and the meteorological and source inputs described in the Appendix are shown in Figures 6 through 11.

Figure 6 shows centerline HCl concentrations for the model calculations where the surface-based inversion indicated by the meteorological measurements was assumed to inhibit the major protion of the stabilized ground cloud from diffusing to the surface. For this reason, the centerline HCl concentrations at the surface are very much lower than concentrations at heights above the surface inversion and fall to less than 0.1 ppm HCl beyond about 2 kilometers from the launch pad. Figure 6 also shows centerline HCl concentrations at the three heights (396m, 701m, and 914m) where the sampling aircraft penetrated the stabilized cloud of exhaust products. Table 2 shows the times and the altitudes at which the aircraft sample runs were made according to the information received from Mr. Scott Wagner of Langley Research Center.

TABLE 2.

SAMPLING AIRCRAFT ALTITUDES AND TIME OF CLOUD PENETRATION

Altitude (m)	Time After Launch (seconds)
396	202*
701	310
914	865
*NOTE: Plotted on Figures 12 and 13	

It should be noted that our estimates for the time required for the cloud to become stabilized at a height of 747 meters is about 275 seconds. For this reason, the aircraft may have sampled the cloud before the cloud stabilized in the sampling run beginning at 202 seconds after launch. Thus, the centerline concentrations shown in Figure 6 for a height of 396 meters should be reasonable. Inspection of Figure 6 shows that there is no difference between estimated concentration levels at heights of 701 and 914 meters above the surface.

In contrast to Figure 6, Figure 7 shows centerline HCl concentrations for the model calculations where the surface-based inversion was assumed not to be present. In this case, material in the major portion of the exhaust cloud is permitted to diffuse to the surface, and surface concentrations are greater than 0.1 ppm HCl to a distance of about 20 kilometers from the launch pad. Concentration at heights above the surface based inversion are also lower than the centerline concentrations at similar heights shown in Figure 6, because the layer through which the cloud can diffuse is correspondingly deeper. Thus, as shown in Figure 7, HCl concentrations at all heights below the marine inversion are less than 0.1 ppm HCl beyond about 20 kilometers from the launch pad.

Figure 8 and 9 show the respective centerline concentrations of CO for the inversion and no-inversion cases. Similarly, Figure 10 and 11 show centerline concentrations of Al_2O_3 for the inversion and no-inversion cases. Because the only difference between the calculations for the three different pollutants is the total source strength of HCl, CO, and Al_2O_3 emitted, these figures show essentially the same features as described above for HCl.

It should be noted that all the results shown in the figures are based on the assumptions that the cloud centroid is at a height above the surface of about 747 meters and that the procedure for estimating the vertical distribution of material in the stabilized ground cloud is valid. Previous experience in estimating concentrations downwind from vehicle launches has shown that the estimation procedure is sensitive to these assumptions in the first 10 kilometers downwind from the source. The differences in measured and estimated concentrations near the cloud centroid would not be expected to be too large, provided the aircraft penetrated the cloud at its centroid. Also, the concentrations shown in the figures are estimated maximum concentrations at the indicated heights and distances. Experience in conducting sampling programs has also shown that it is extremely difficult for an aircraft pilot to determine the position of the cloud center. Finally, the speed with which the aircraft flies through the cloud and the response time of the measurement devices must be considered in comparing estimated and measured concentrations.

Figures 12 and 13 show curves as were fitted to exhaust cloud rise rate and horizontal growth data extracted from time lapse photographs. Two cameras were used to take photographs at a frequency of 2 frames per second. One camera was mounted 208 degrees clockwise from true North about launch pad center at a distance of 1600 m (5250 ft) from the pad.

The second camera was situated at an angle of 303° clockwise and at a distance of 2820 m (9250 ft) from launch pad center. This arrangement positioned the camera approximately orthogonal with the pad center as the common intersect. Data were only taken from the film to about 4 minutes after launch in that this Delta-Thor was a nighttime launch and the cloud could not be very well illuminated by the flood lights beyond that time period. Improvements can be expected in photographing such clouds at night from the experience gained from this first attempt.

CONCLUSIONS

The Delta-Thor Telsat-A mission launched on November 9, 1973, at Cape Kennedy provided the opportunity to demonstrate the usefulness of the MSFC Multilayer Diffusion Model and provide ground level concentrations of exhaust by-products emitted during normal vehicle launches. Centerline concentrations on the ground for HCl exceed .1 ppm out to a distance of 20 km for the no surface inversion case. For both CO and Al_2O_3 this value of .1 ppm is predicted out to almost 40 km downwind.

The ground cloud was monitored quite well even though the vehicle was launched at night. The use of a large number of flood lights made it possible to track and photograph the stabilized ground cloud for several minutes.

The information in this report as well as the many similar studies as referenced makes it convincing that the behavior of vehicle exhaust clouds can be predicted. Subsequently, launch vehicle constraints to safeguard against the possibility of exposing any life to excessive dosages of toxic exhaust by-products, can be properly outlined. This is especially necessary when plans are made to launch large vehicle configurations such as the Space Shuttle.

This study has also shown that it is convenient to have a sufficient number of diffusion models so that all atmospheric conditions can be considered. In addition, the multilayer concept has added significant realism to this work where atmospheric layer structures can be treated.

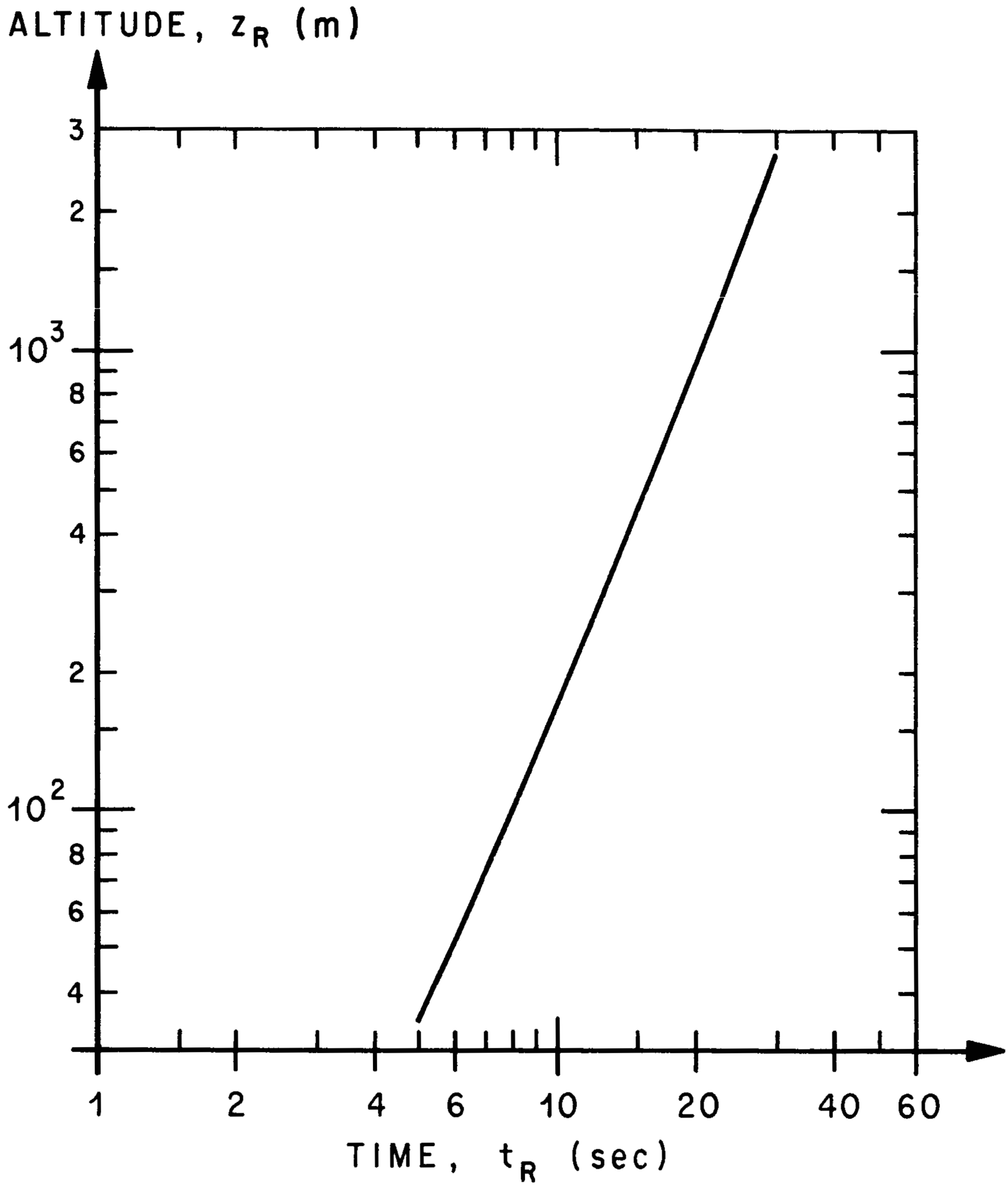

FIGURE 1. ALTITUDE OF THE DELTA-THOR VEHICLE AS A FUNCTION OF TIME AFTER IGNITION.

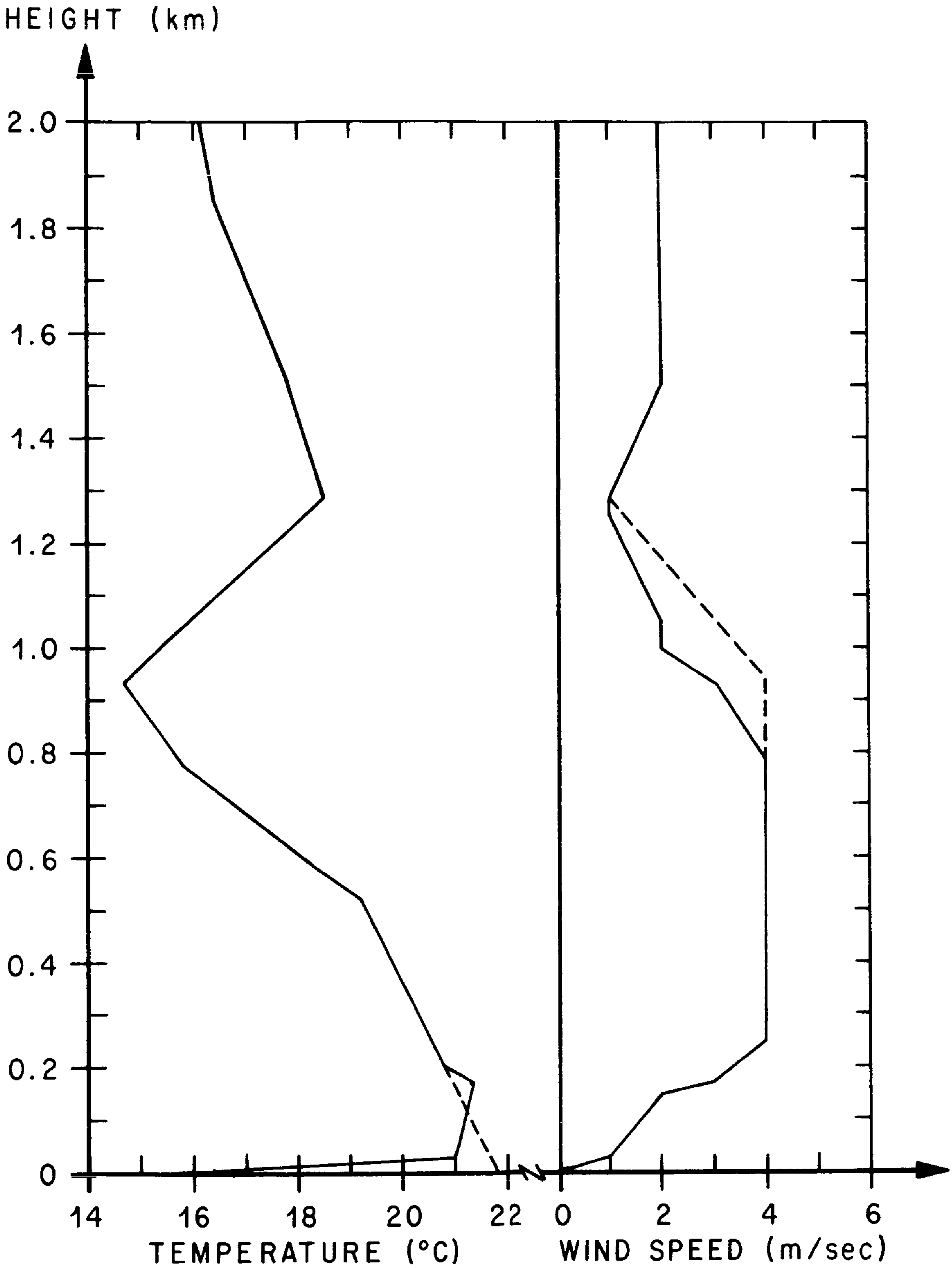

Figure 2. TEMPERATURE AND WIND SPEED DATA (SOLID LINES) FROM RAWINSONDE AND 150 M TOWER DATA AT 2018 EST NOVEMBER 9, 1972. DASHED LINES REPRESENT MODIFICATIONS MADE FOR USE IN CALCULATING GROUND-LEVEL CONCENTRATIONS IN THE ABSENCE OF A DEEP GROUND-BASED INVERSION.

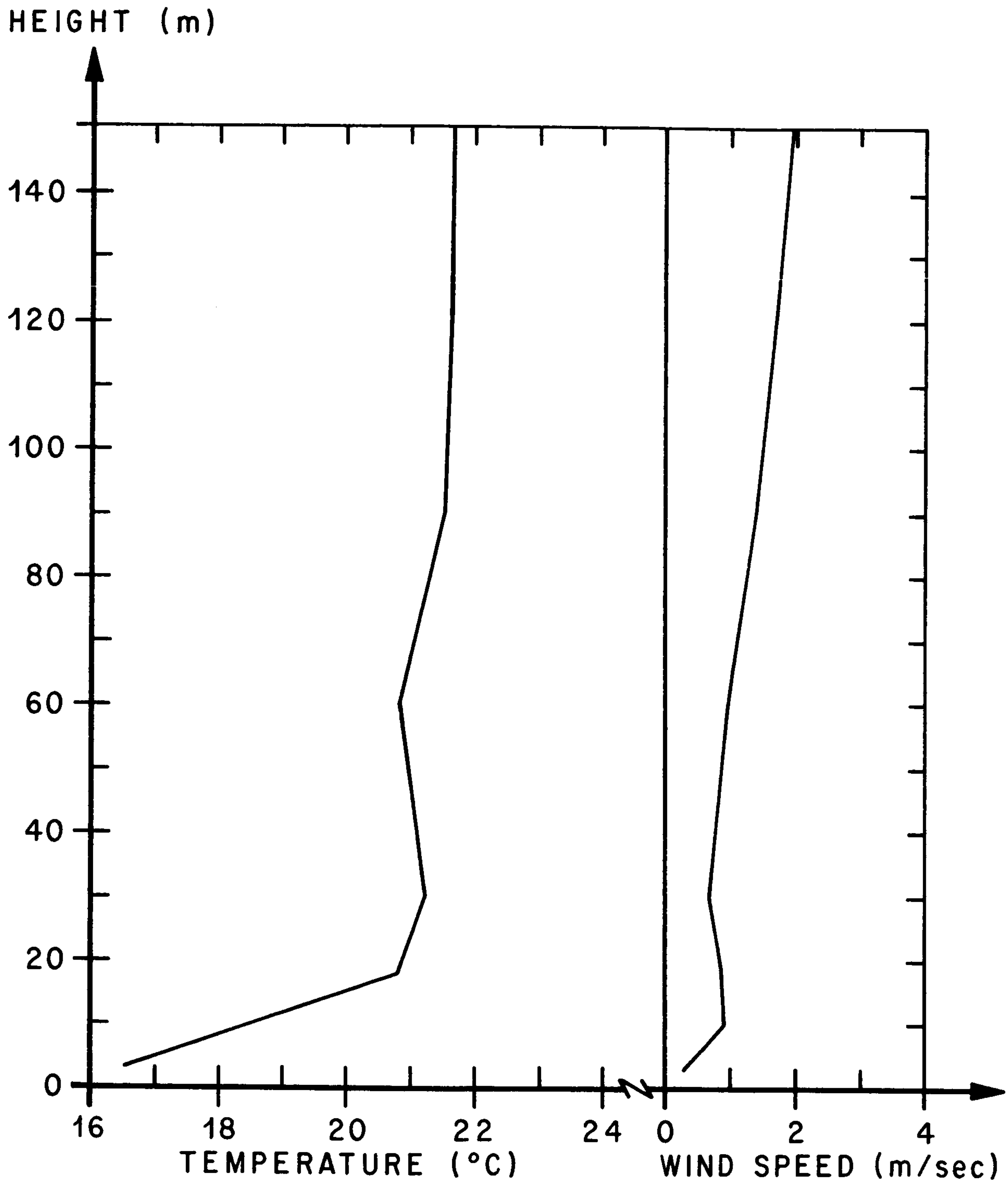

FIGURE 3. TEMPERATURE AND WIND SPEED MEASURED ON THE NASA 150 METER GROUND WIND TOWER AT LAUNCH TIME.

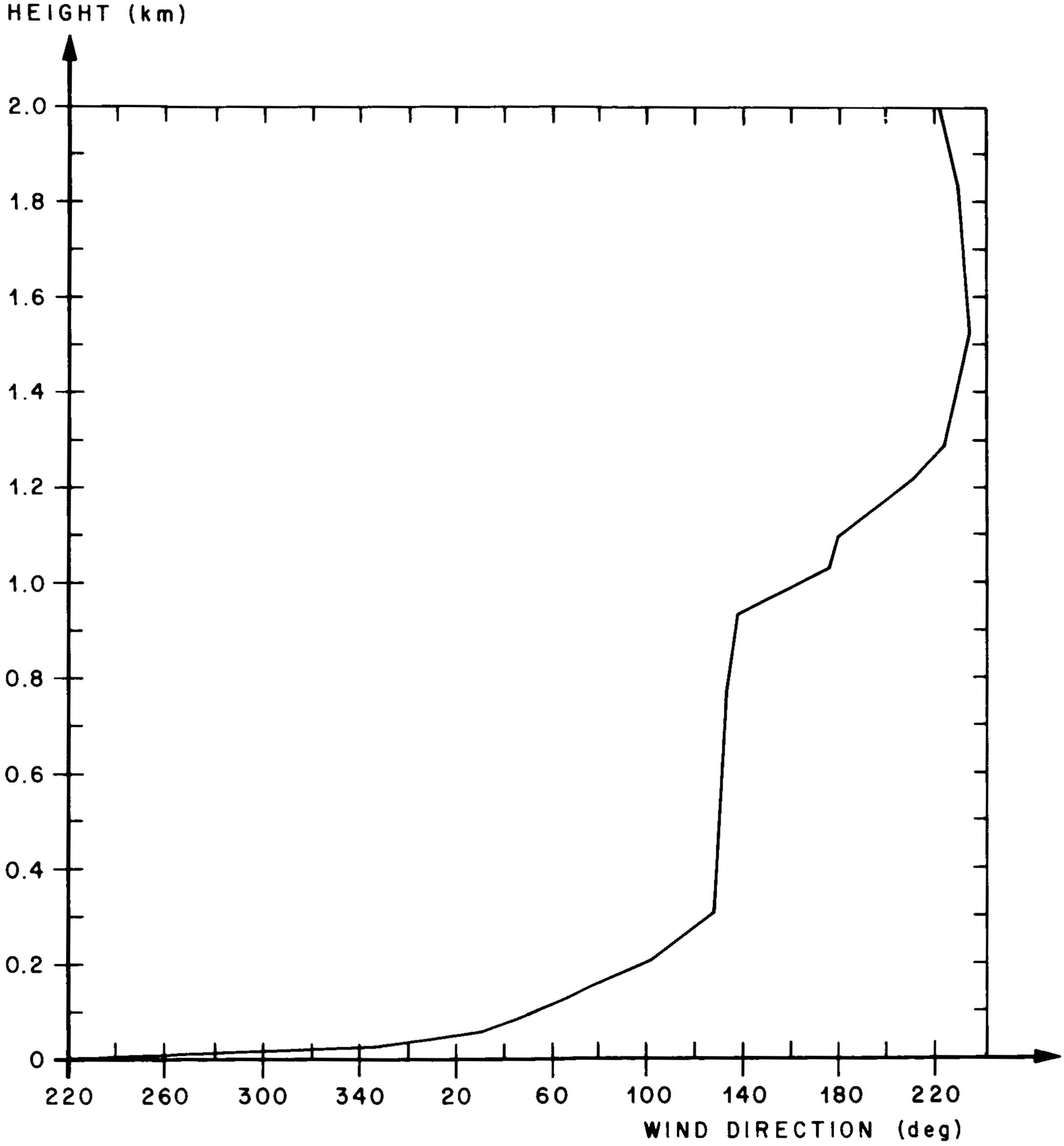

FIGURE 4. WIND DIRECTION MEASUREMENTS FROM RAWINSONDE AND TOWER DATA ON NOVEMBER 9, 1972 AT 2018 EST

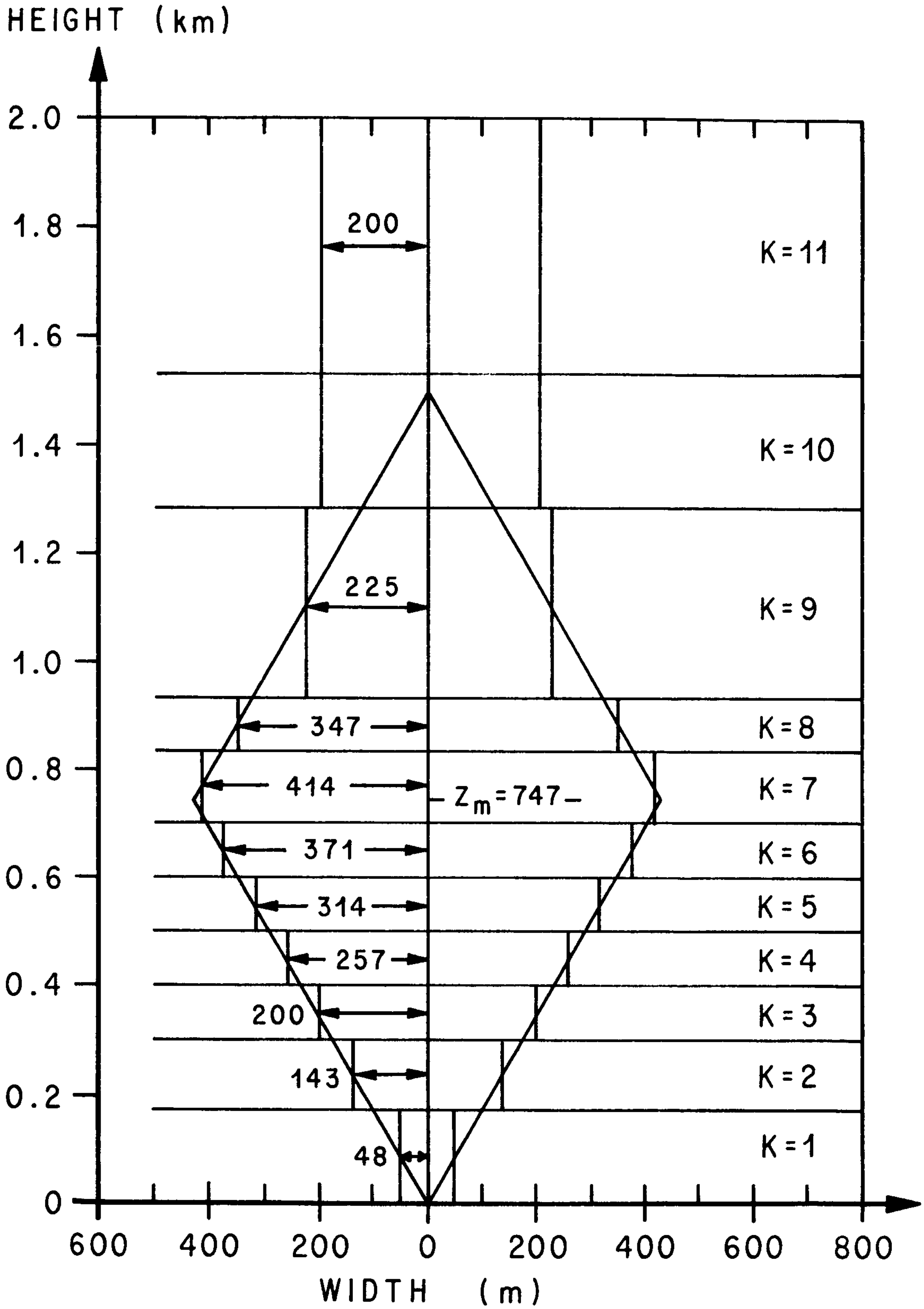

FIGURE 5. CALCULATED DIMENSIONS OF THE STABILIZED CLOUD OF EXHAUST PRODUCTS FOR THE NOVEMBER 9, 1972 LAUNCH OF A DELTA-THOR VEHICLE. HEIGHT OF THE CLOUD CENTROID IS 747 METERS.

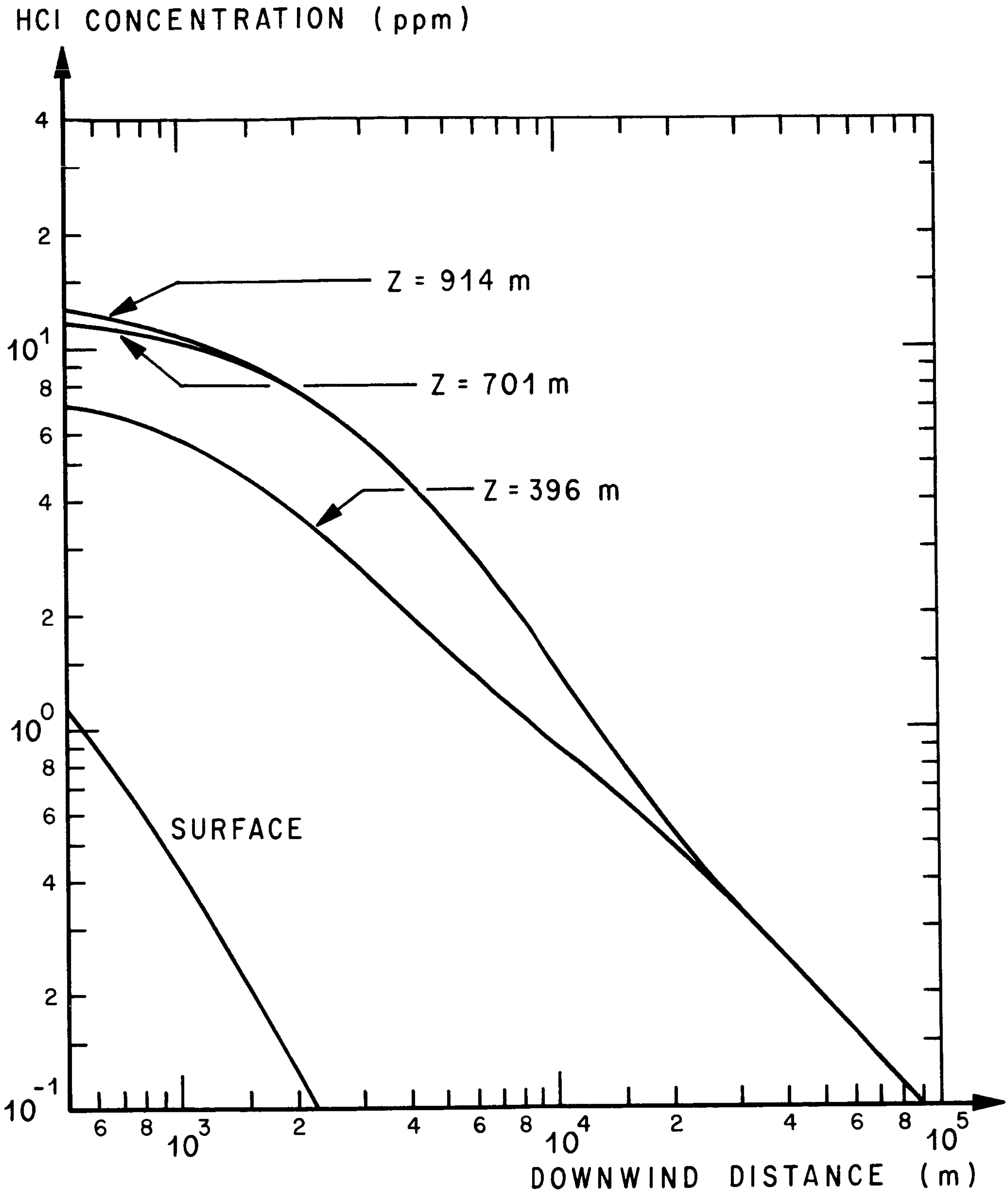

FIGURE 6. CENTERLINE HCl CONCENTRATIONS AT THE SURFACE AND AT THE HEIGHTS FLOWN BY THE SAMPLING AIRCRAFT FOR THE DELTA-THOR LAUNCH OF NOVEMBER 9, 1972 AND FOR THE SURFACE-INVERSION CASE.

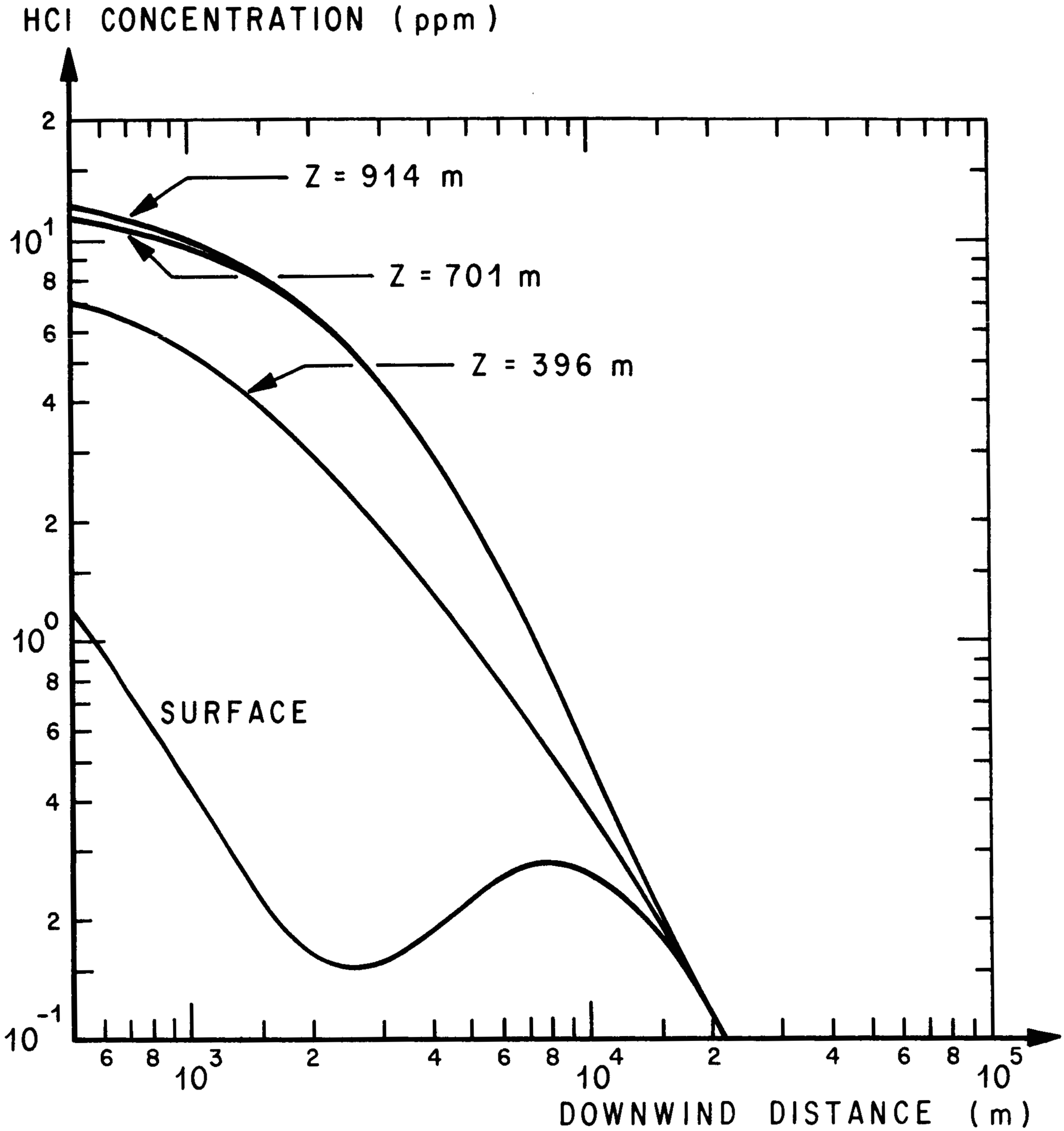

FIGURE 7. CENTERLINE HCl CONCENTRATIONS AT THE SURFACE AND AT THE HEIGHTS FLOWN BY THE SAMPLING AIRCRAFT FOR THE DELTA-THOR LAUNCH OF NOVEMBER 9, 1972 AND FOR THE NO SURFACE-INVERSION CASE.

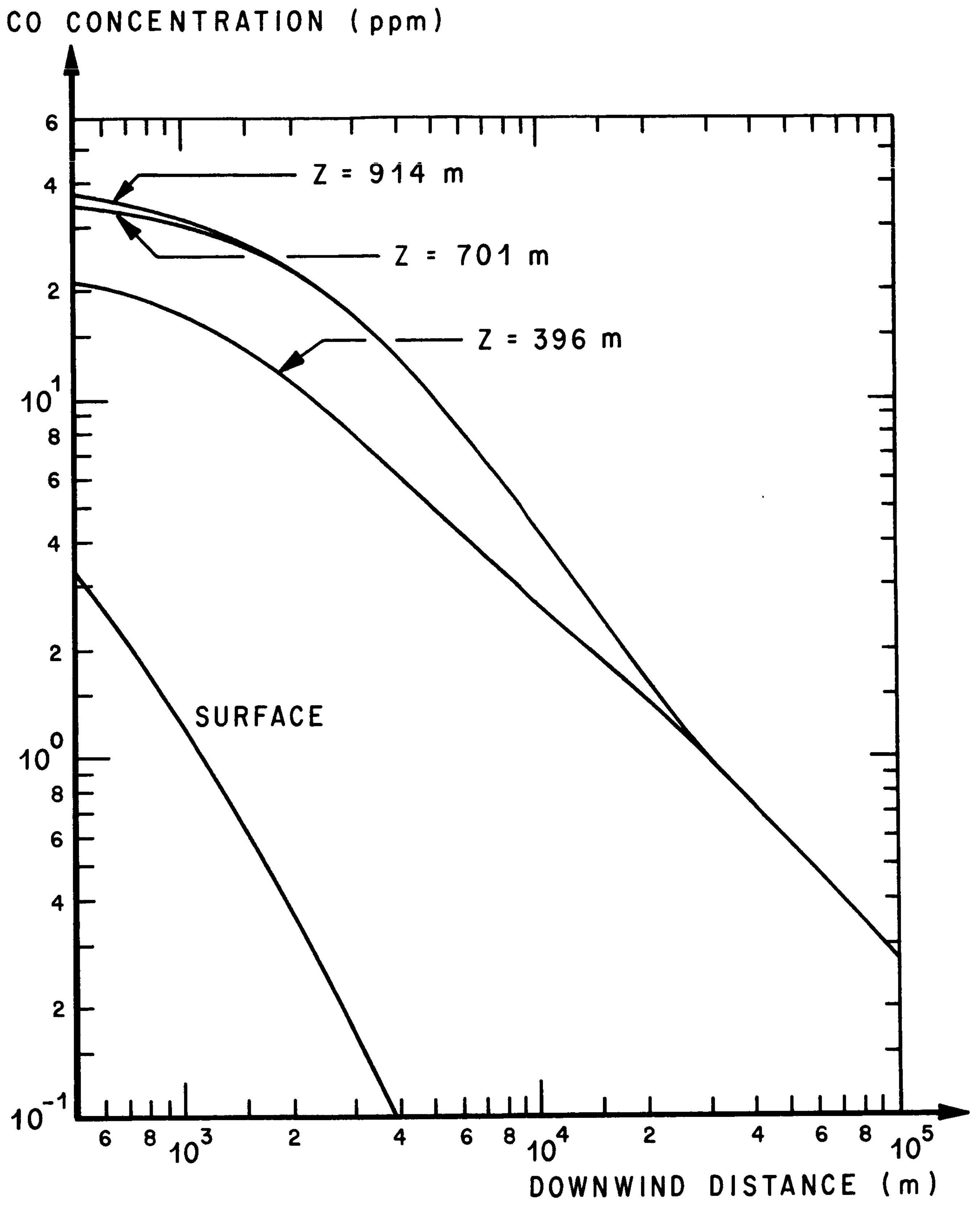

FIGURE 8. CENTERLINE CO CONCENTRATIONS AT THE SURFACE AND AT THE HEIGHTS FLOWN BY THE SAMPLING AIRCRAFT FOR THE DELTA-THOR LAUNCH OF NOVEMBER 9, 1972 AND FOR THE SURFACE-INVERSION CASE.

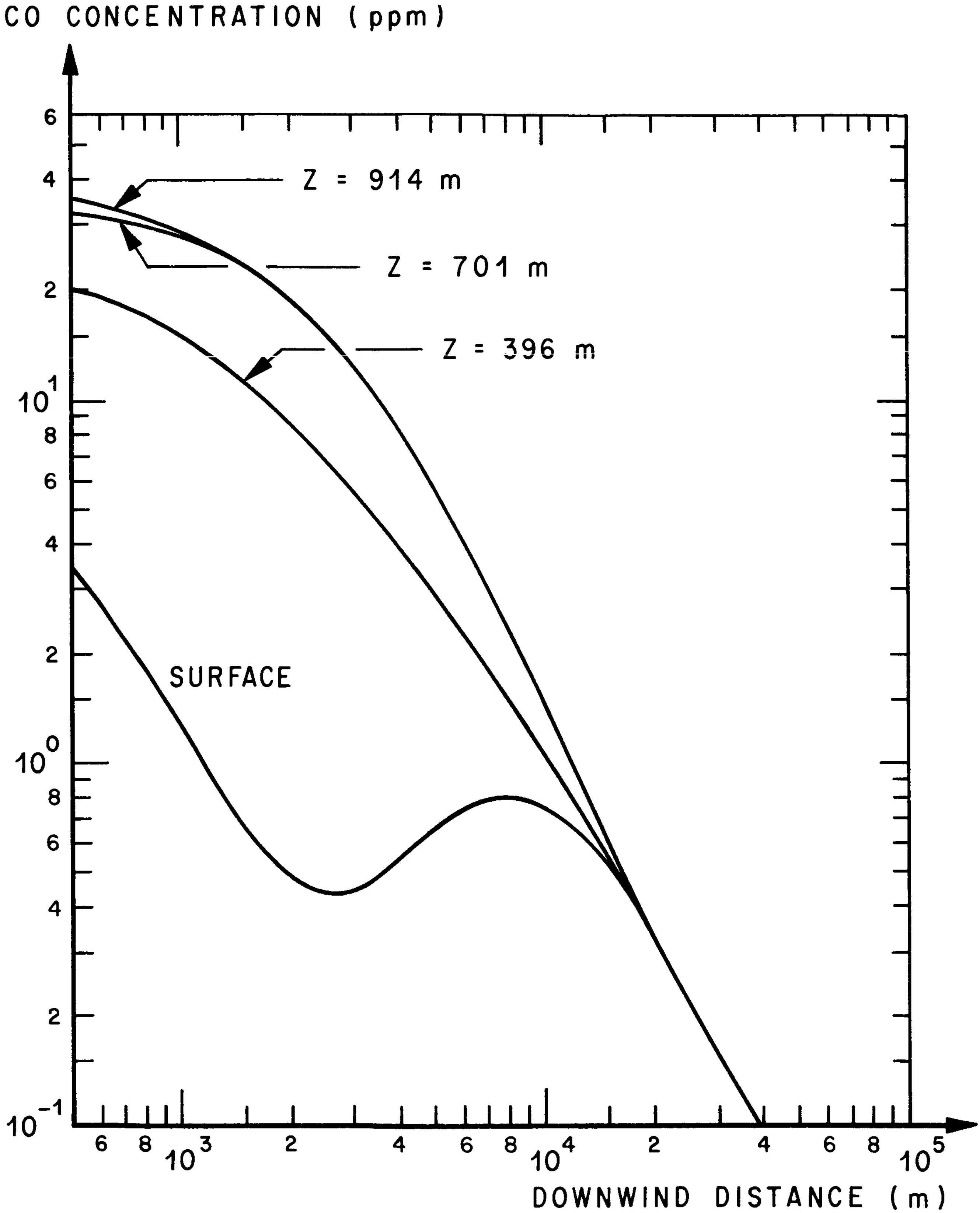

FIGURE 9. CENTERLINE CO CONCENTRATIONS AT THE SURFACE AND AT THE HEIGHTS FLOWN BY THE SAMPLING AIRCRAFT FOR THE DELTA-THOR LAUNCH OF NOVEMBER 9, 1972 AND FOR THE NO SURFACE-INVERSION CASE.

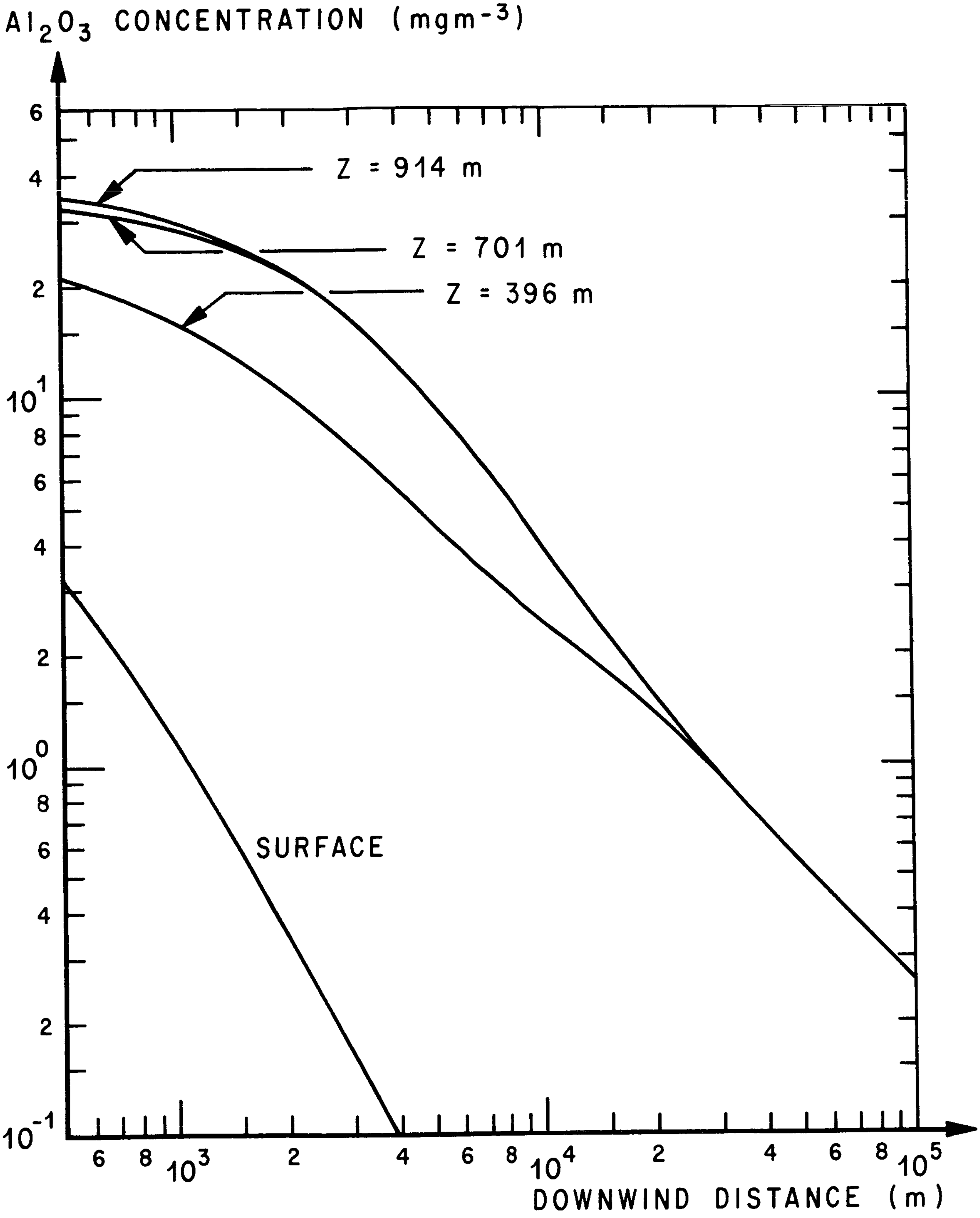

FIGURE 10. CENTERLINE Al_2O_3 CONCENTRATIONS AT THE SURFACE AND AT THE HEIGHTS FLOWN BY THE SAMPLING AIRCRAFT FOR THE DELTA-THOR LAUNCH OF NOVEMBER 9, 1972 AND FOR THE SURFACE-INVERSION CASE.

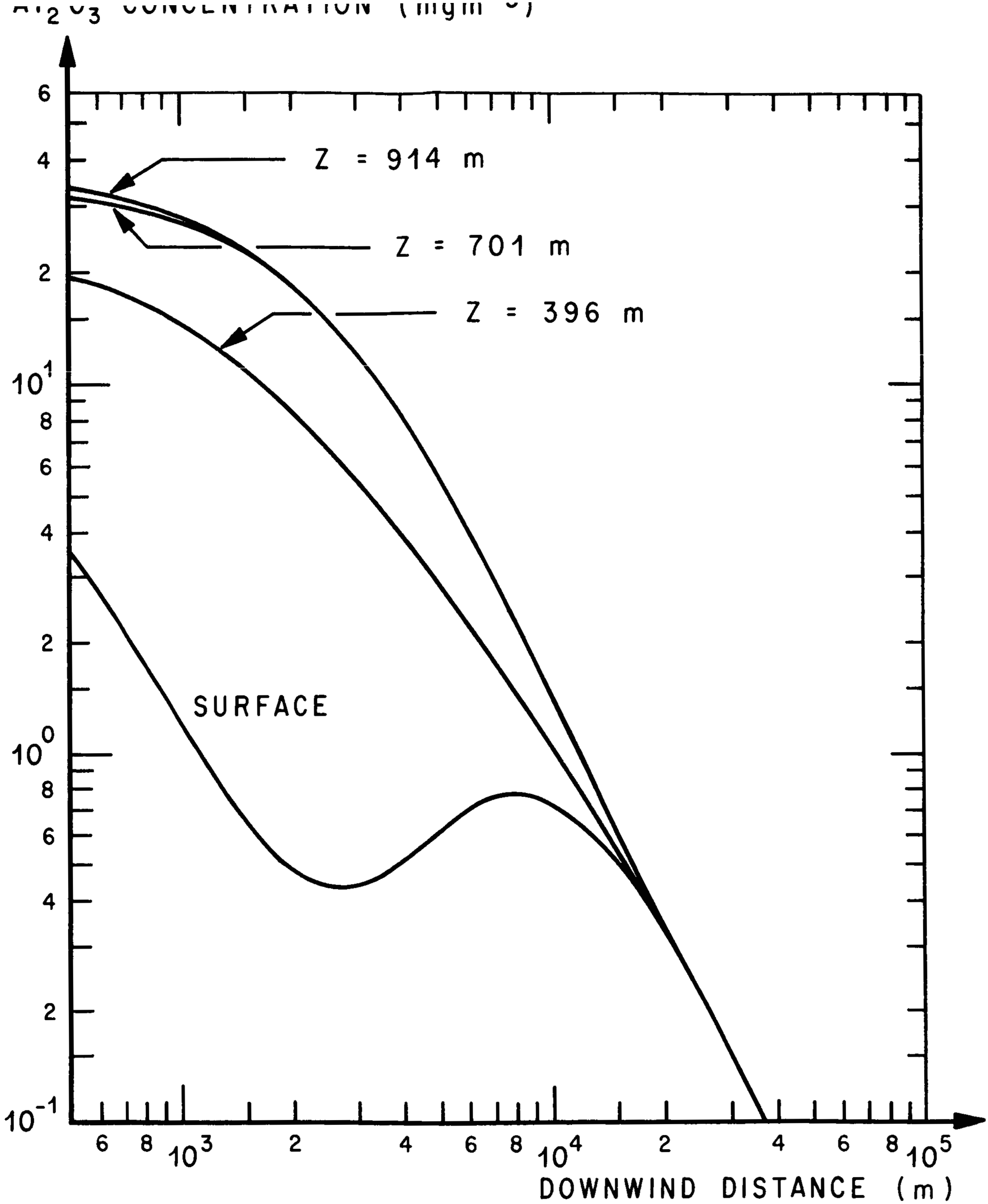

FIGURE 11. CENTERLINE Al_2O_3 CONCENTRATIONS AT THE SURFACE AND AT THE HEIGHTS FLOWN BY THE SAMPLING AIRCRAFT FOR THE DELTA-THOR LAUNCH OF NOVEMBER 9, 1972 AND FOR THE NO SURFACE-INVERSION CASE.

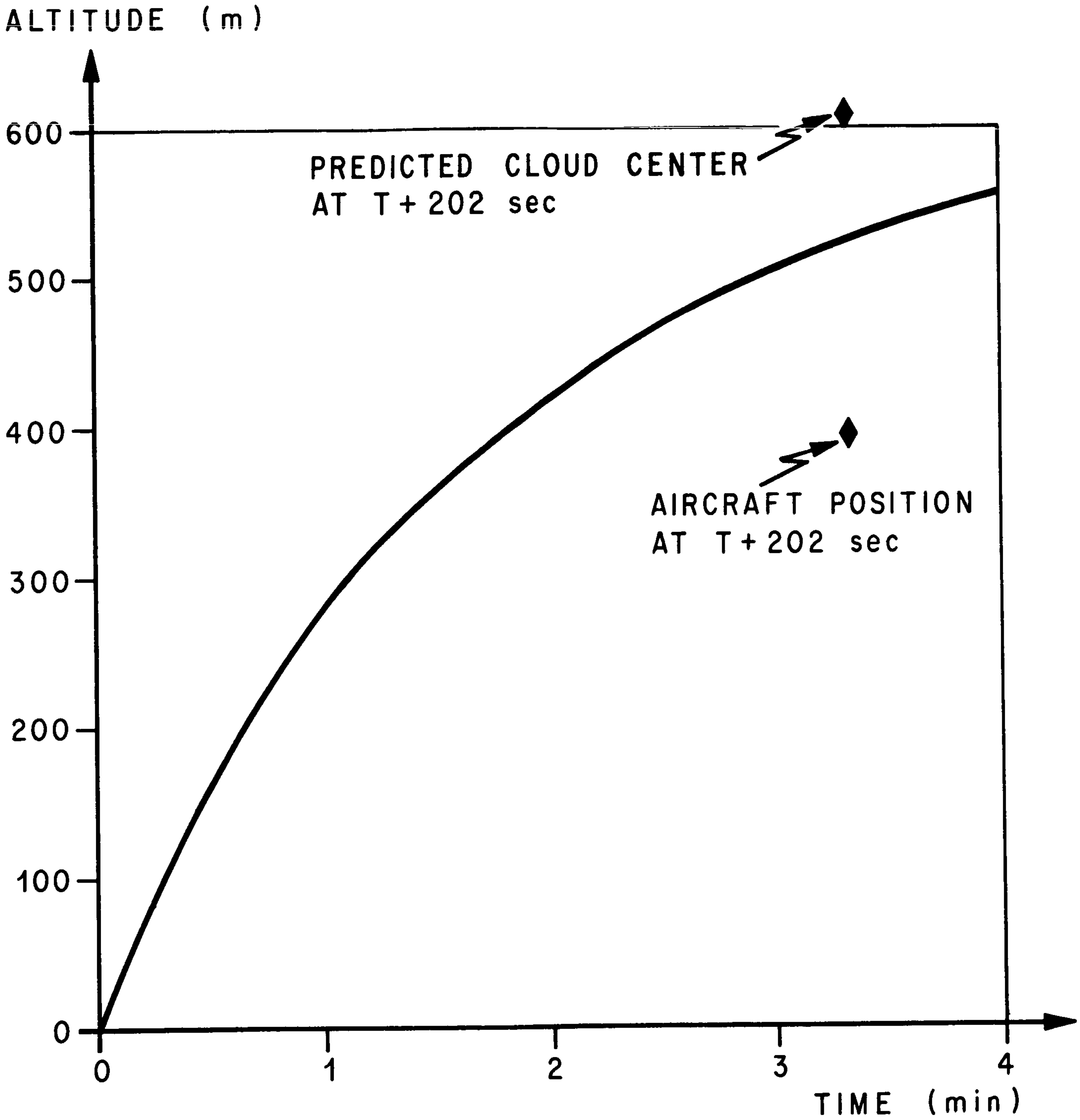

FIGURE 12. EXHAUST CLOUD ALTITUDE VERSUS TIME FOR DELTA-THOR TELSAT-A LAUNCH ON NOVEMBER 9, 1972 (2014 EST) AT CAPE KENNEDY, FLORIDA

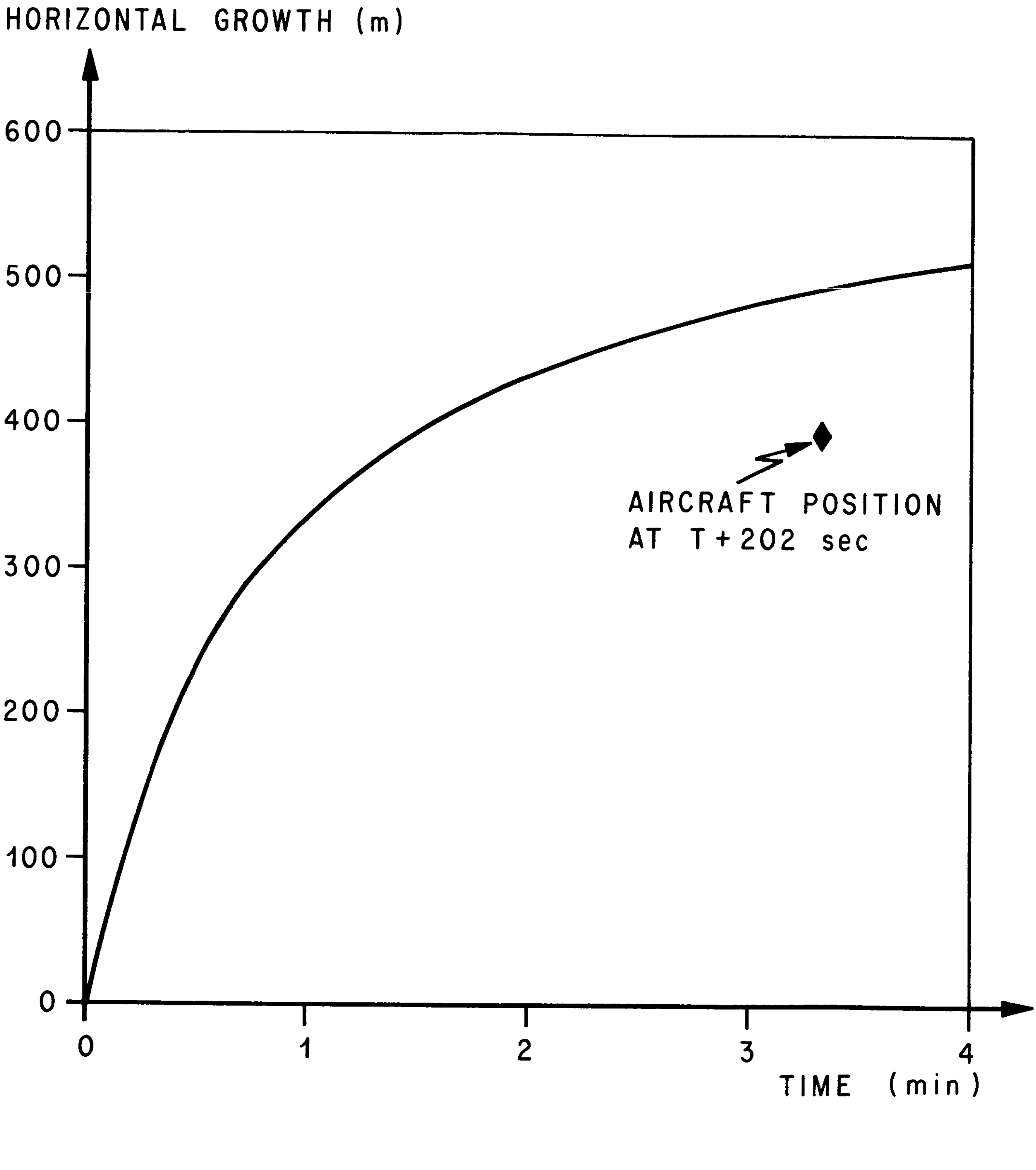

FIGURE 13. HORIZONTAL GROWTH OF GROUND CLOUD VERSUS TIME FOR DELTA-THOR LAUNCH ON NOVEMBER 9, 1972 (2014 EST) AT CAPE KENNEDY, FLORIDA.

APPENDIX. METEOROLOGICAL AND SOURCE MODEL INPUTS

Meteorological and source model inputs used in the concentration calculations are given in Table A for the inversion case and in Table B for the no-inversion case. The source inputs in the tables were calculated using the procedures described in Sections 3 and 4 of the technical memorandum. The requisite values of mean wind speed, wind direction, temperature and pressure were obtained from the rawinsonde and tower measurements described in Section 2. Measurements from the NASA 150 m Ground Wind Tower data indicated the standard deviation of the azimuth wind angle fluctuations for a 10-minute period at a height of 18 meters was about nine degrees. The following general rules were used to specify the vertical profiles of the azimuth $\left(\sigma_A\{\tau_{oK}\}\right)$ and elevation $\left(\sigma_E\right)$ wind angle fluctuations.

<u>In the surface mixing layer $z < H_m$:</u>

(1) If the wind speed is constant or decreases with height in the layer, $\sigma_A\{\tau_{oK}\}$ is held constant with height in the layer.

(2) If the wind speed increases with height, $\sigma_A\{\tau_{oK}\}$ is decreased with height according to the relationship

$$\sigma_A\{\tau_{oK}, z\} = \sigma_{AR}\{\tau_{oK}\}\left(\frac{z}{z_R}\right)^{-p} \tag{A-1}$$

where p = wind profile exponent

$$= \frac{\ell n\left[\bar{u}_{TK}/\bar{u}_R\right]}{\ell n\left[z_{TK}/z_R\right]} \tag{A-2}$$

$\bar{u}_{TK}$ = mean wind speed at the top of the layer z_{TK}

$\bar{u}_R$ = mean wind speed at the reference height z_R

<u>In layers above the surface mixing layer $\left(z > H_m\right)$:</u>

(1) If the wind speed is constant or decreases with height in a stable layer, $\sigma_A\{\tau_{oK}\}$ is decreased linearly with height from the value at the base of the layer to a value of one degree at the top of the layer.

TABLE A. METEOROLOGICAL AND SOURCE MODEL INPUTS FOR THE DELTA-THOR LAUNCH OF NOVEMBER 9, 1972 - INVERSION CASE

Parameter	Units	Layer										
		1	2	3	4	5	6	7	8	9	10	11
Q_K - HCl	ppm m^2	1.541×10^4	1.152×10^5	4.087×10^5	9.721×10^5	1.801×10^6	2.600×10^6	2.883×10^6	2.305×10^6	7.036×10^5	1.951×10^4	1.200×10^2
- CO	ppm m^2	4.506×10^4	3.368×10^5	1.195×10^5	2.841×10^6	5.264×10^6	7.599×10^6	8.429×10^6	6.737×10^6	2.057×10^6	5.703×10^4	3.509×10^2
- Al_2O_3	mg m^{-1}	4.315×10^4	3.226×10^5	1.144×10^6	2.721×10^6	5.041×10^6	7.276×10^6	8.071×10^6	6.452×10^6	1.970×10^6	5.461×10^4	3.361×10^2
z_R	m	18										
$\bar{u}_R$	m sec^{-1}	0.9										
$\sigma_{AR}\{\tau_{oK}\}$	deg	9.0										
σ_{ER}	deg	7.7										
τ_{oK}	sec	600										
τ_K	sec	275.1										
$\sigma_{ATK}\{\tau_{oK}\}$	deg	3.85	3.11	2.79	2.56	2.39	2.26	2.11	2.02	1.0	1.0	1.0
$\sigma_{ABK}\{\tau_{oK}\}$	deg	20.65	3.85	3.11	2.79	2.56	2.39	2.26	2.11	2.02	1.0	1.0
$\sigma_{yo}\{K\}$	m	22.53	62.30	92.79	119.30	145.81	172.30	192.60	161.46	101.80	93.0	93.0
α_K		1	1	1	1	1	1	1	1	1	1	1
σ_{ETK}	deg	3.29	2.66	2.39	2.19	2.04	1.93	1.81	1.73	0.85	0.85	0.85
σ_{EBK}	deg	17.67	3.29	2.66	2.39	2.19	2.04	1.93	1.81	1.73	0.86	0.85
$\sigma_{zo}\{K\}$	m	49.07	37.53	28.87	28.87	28.87	28.87	38.96	28.87	101.04	70.73	135.68
$\sigma_{xo}\{K\}$	m	22.53	62.30	92.79	119.30	145.81	172.30	192.60	161.46	101.80	93.0	93.0

TABLE A. (continued)

Parameter	Units	Layer										
		1	2	3	4	5	6	7	8	9	10	11
β_K		1	1	1	1	1	1	1	1	1	1	1
z_{TK}	m	170	300	400	500	600	700	835	935	1285	1530	2000
z_{BK}	m	2	170	300	400	500	600	700	835	935	1285	1530
$\bar{u}_{TK}$	m sec^{-1}	3.0	4.0	4.0	4.0	4.0	4.0	3.6	3.0	1.0	2.0	2.0
$\bar{u}_{BK}$	m sec^{-1}	0.3	3.0	4.0	4.0	4.0	4.0	4.0	3.6	3.0	1.0	2.0
θ_{TK}	deg	129	130	130	130	131	132.5	135	138	224	236	223
θ_{BK}	deg	129	129	130	130	130	131	132.5	135	138	224	236
Φ_{TK}	^oK	294.8	295.0	295.5	296.0	295.8	295.4	295.3	295.6	303.0	304.6	307.8
Φ_{BK}	^oK	287.7	294.8	295.0	295.5	296.0	295.8	295.4	295.3	295.6	303.0	304.6
T_{TK}	^oK	294.6	293.5	293.0	292.5	291.3	290.0	288.6	287.9	291.7	290.8	289.3
T_{BK}	^oK	289.0	294.6	293.5	293.0	292.5	291.3	290.0	288.6	287.9	291.7	290.8
P_{TK}	mb	997.5	982.5	971.0	959.7	948.0	937.5	923.0	912.3	875.4	850.0	805.1
P_{BK}	mb	1016.3	997.5	982.5	971.0	959.7	948.0	937.5	923.0	912.3	875.4	850.0
t*	sec		1	1	1	1	1	1	1			
Model No.		1	5*	5*	5*	5*	5*	5*	5*	1	1	1

*This is Model 4 in the revised report [2].

TABLE B. METEOROLOGICAL AND SOURCE MODEL INPUTS FOR THE DELTA-THOR LAUNCH OF NOVEMBER 9, 1972 - NO-INVERSION CASE

Parameter	Units	Layer										
		1	2	3	4	5	6	7	8	9	10	11
Q_K - HCl	ppm m^2	1.541×10^4	1.152×10^5	4.087×10^5	9.721×10^5	1.801×10^6	2.600×10^6	2.883×10^6	2.305×10^6	7.036×10^5	1.951×10^4	1.200×10^2
- CO	ppm m^2	4.506×10^4	3.368×10^5	1.195×10^5	2.841×10^6	5.264×10^6	7.599×10^6	8.429×10^6	6.737×10^6	2.057×10^6	5.703×10^4	3.509×10^2
- Al_2O_3	mg m^{-1}	4.315×10^4	3.226×10^5	1.144×10^6	2.721×10^6	5.041×10^6	7.276×10^6	8.071×10^6	6.452×10^6	1.970×10^6	5.461×10^4	3.361×10^2
z_R	m	18										
$\bar{u}_R$	m sec^{-1}	0.9										
$\sigma_{AR}\{\tau_{oK}\}$	deg	9.0										
σ_{ER}	deg	7.7										
τ_{oK}	sec	600										
τ_K	sec	275.1										
$\sigma_{ATK}\{\tau_{oK}\}$	deg	2.70	2.70	2.70	2.70	2.70	2.70	2.70	1.0	1.0	1.0	1.0
$\sigma_{ABK}\{\tau_{oK}\}$	deg	29.22	2.70	2.70	2.70	2.70	2.70	2.70	2.70	1.0	1.0	1.0
$\sigma_{yo}\{K\}$	m	22.53	62.30	92.79	119.30	145.81	172.30	192.60	161.46	101.80	93.0	93.0
α_K		1	1	1	1	1	1	1	1	1	1	1
σ_{ETK}	deg	2.31	2.31	2.31	2.31	2.31	2.31	2.31	0.85	0.85	0.85	0.85
σ_{EBK}	deg	25.00	2.31	2.31	2.31	2.31	2.31	2.31	2.31	0.85	0.85	0.85
$\sigma_{zo}\{K\}$	m	49.07	37.53	28.87	28.87	28.87	28.87	38.97	28.87	101.04	70.73	135.68
$\sigma_{xo}\{K\}$	m	22.53	62.30	92.79	119.30	145.81	172.30	192.60	161.46	101.80	93.0	93.0

TABLE B. (Continued)

Parameter	Units	Layer										
		1	2	3	4	5	6	7	8	9	10	11
β_K		1	1	1	1	1	1	1	1	1	1	1
z_{TK}	m	170	300	400	500	600	700	835	935	1285	1530	2000
z_{BK}	m	2	170	300	400	500	600	700	835	935	1285	1530
$\bar{u}_{TK}$	m sec^{-1}	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	1.0	2.0	2.0
$\bar{u}_{BK}$	m sec^{-1}	0.39	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	1.0	2.0
θ_{TK}	deg	129	130	130	130	131	132.5	135	138	224	236	223
θ_{BK}	deg	129	129	130	130	130	131	132.5	135	138	224	236
Φ_{TK}	^{o}K	294.5	295.0	295.5	296.0	295.8	295.4	295.3	295.6	303.0	304.6	307.8
Φ_{BK}	^{o}K	293.6	294.5	295.0	295.5	296.0	295.8	295.4	295.3	295.6	303.0	304.6
T_{TK}	^{o}K	294.3	293.5	293.0	292.5	291.3	290.0	288.6	287.9	291.7	290.8	289.3
T_{BK}	^{o}K	295.0	294.3	293.5	293.0	292.5	291.3	290.0	288.6	287.9	291.7	290.8
P_{TK}	mb	997.5	982.5	971.0	959.7	948.0	937.5	923.0	912.3	875.4	850.0	805.1
P_{BK}	mb	1016 3	997.5	982.5	971.0	959.7	948.0	937.5	923.0	912.3	875.4	850.0
t*	sec	1	1	1	1	1	1	1	1			
Model No.		5*	5*	5*	5*	5*	5*	5*	5*	1	1	1

*This is Model 4 in the revised report [2].

(2) If the wind speed is constant or decreases with height in an unstable layer, $\sigma_A\{\tau_{oK}\}$ is held constant with height in the layer

(3) If the wind speed increases with height in an unstable or stable layer, $\sigma_A\{\tau_{oK}\}$ is decreased with height according to the relationship

$$\sigma_A\{\tau_{oK}, z\} = \sigma_{ABK}\{\tau_{oK}\} \left(\frac{z}{z_{BK}}\right)^{-p_K} \tag{A-3}$$

where

$$p_K = \frac{\ell n\left[\bar{u}_{TK}/\bar{u}_{BK}\right]}{\ell n\left[z_{TK}/z_{BK}\right]}$$

$\bar{u}_{BK}$ = mean wind speed at the base of the layer z_{BK}

It should be noted that $\sigma_A\{\tau_{oK}\}$ is not permitted to be less than one degree.

Values of the standard deviation of elevation wind angle fluctuations are set equal to $\sigma_A\{\tau_K\}$; that is,

$$\sigma_E = \sigma_A\{\tau_{oK}\} \left(\frac{\tau_K}{\tau_{oK}}\right)^{1/5} \tag{A-4}$$

where

τ_{oK} = reference time period over which $\sigma_A\{\tau_{oK}\}$ is measured

τ_K = source function time in the layer

In the concentration calculations, τ_K for normal launches was set equal to the time t_H required for the exhaust cloud to reach stabilization which is obtained from Equation 2 in the body of the report. The value of the diffusion parameters α and β were set equal to unity in all cases.

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